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Cortical Surface Area and Cortical Thickness Demonstrate Differential Structural Asymmetry in Auditory-Related Areas of the Human Cortex

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Keywords: auditory-related cortex, cortical surface area, cortical thickness, hemispheric asymmetry

Introduction

The human auditory cortex should be considered a region of specific interest for cognitive neuroscience as its functioning may be linked to the language network. Even though the functional circuits, as well as the micro- and macroscopic architecture of the auditory cortex in nonhuman primates, namely macaques and chimpanzees, have been thoroughly investigated (Pandya 1995; Rauschecker et al. 1995, 1997; Kaas and Hackett 2000; Hackett et al. 2001; Hackett and Kaas 2004), it is not yet clear whether this knowledge is applicable to the human brain. According to cytoarchitectonic and macroscopic studies, the neuroanatomy of the auditory-related cortex of humans and nonhuman primates is substantially different (Hackett et al. 2001; Fullerton and Pandya 2007), for example, with respect to the position and borders of the auditory core region (Da Costa et al. 2011). Furthermore, previous research has demonstrated that, in comparison with the functionally defined auditory cortex in macaques, the area pertaining to the functionally defined auditory cortex in humans has expanded by 10-fold when compared with apes during the course of evolution (Woods et al. 2010). Thus, it is more than plausible that the evolution of speech primarily accounts for the differences found in the auditory-related cortical architecture of humans and nonhuman primates. In addition, the human auditory cortex demonstrates structural asymmetries pertaining to the microscopic organization of neuronal microcolumns, which are not apparent in chimpanzees and macaques (Buxhoeveden and Casanova 2000; Galuske et al. 2000; Buxhoeveden et al. 2001). Attempts to relate hemispheric differences in neuroanatomical architecture to functional lateralization suggest that the leftward structural macroscopic asymmetry of particular one auditory-related cortical region, namely the planum temporale (PT), should be considered the left hemisphere's dominant "speech" neural substrate (Galaburda et al. 1978). In addition, findings from a multitude of reports illustrate a human auditory-related cortex consisting of distinct portions that exhibit a strong leftward structural asymmetry (Penhune et al. 1996; Beaton 1997; Shapleske et al. 1999; Eckert 2004; Josse et al. 2006, 2009; Eckert et al. 2008; Schneider et al. 2009). Nevertheless, a systematic and comparative evaluation of these recent neuroanatomical studies is problematic for several reasons. First, different magnetic resonance imaging (MRI)-based techniques were used to measure the asymmetry of various brain structures associated with language mechanisms, namely (semi-) manual in vivo morphometry (Jancke and Steinmetz 1993; Foundas et al. 1994, 1995, 2002; Jancke et al. 1994; Penhune et al. 1996; Knaus et al. 2006) and postmortem morphometry (Galaburda et al. 1978; Anderson et al. 1999; Harasty et al. 2003). One major shortcoming of the time-consuming measurements employed by those morphometric studies is that only data from single, distinct portions of the auditory-related cortex, for example, the PT (Dorsaint-Pierre et al. 2006; Dos Santos Sequeira et al. 2006; Eckert et al. 2006) were reported. This form of methodology becomes problematic if one aims to learn more about the neuroarchitectonic differences and similarities of the adjacent regions (Heschl's gyrus, HG; Heschl's sulcus, HS; PT; planum polare, PP; and lateral superior temporal gyrus, STG) that form the auditory-related cortex. Secondly, it has been emphasized that considerable interindividual anatomical variability of auditory-related perisylvian regions (Rademacher et al. 2001; Tzourio-Mazoyer et al. 2004; Desai et al. 2005) enhance the difficulty of finding consistent and reliable results in the relatively small samples that postmortem studies typically consist of (Westbury et al. 1999). Thirdly, due to a lack of compatibility, there was no agreement regarding the extent to which researchers should compare, evaluate, and interpret macroscopic or microscopic measurement data pertaining to structural architecture (Hackett et al. 2001). Thus, it came as no surprise when an automatic and observer-independent approach, namely voxel-based morphometry (VBM), was suggested as an ideal tool to investigate gray matter (GM) and

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white matter (WM) architecture in large samples of in vivo collected brain scans (Ashburner and Friston 2000). In recent years, this method explores local differences in cortical structure between groups that vary either as a function of learning-dependent plasticity (Golestani et al. 2007), life-span sensory deprivation (Penhune et al. 2003; Mühlau et al. 2006), or brain pathology (Vargha-Khadem et al. 1998; Watkins et al. 2002). Based on a voxel-by-voxel comparison methodology, the VBM approach allows researchers to identify global, regional, or local hemispheric differences in GM and WM within or between groups. In particular, studies employing the automated VBM technique are considered appropriate for revealing local structural cortical asymmetries in GM volume that reflect functional lateralization (Good et al. 2001; Watkins et al. 2001). Nevertheless, this proposal has been challenged, recently, primarily for methodological reasons. Notably, one should be aware that the vast majority of VBM-based studies rely on cortical volume (CV) as an anatomical marker for brain asymmetry. However, as Panizzon et al. (2009) recently argued, CV is the product of surface and thickness. Therefore, if these variables run in the opposite direction, CV measurements could be confounded and asymmetry measurements might be obscured. Among others, Lyttelton et al. (2009) empirically disentangled surface area measurements from the quantification of thickness. In sustenance of this view, Bermudez et al. (2009) demonstrated that the perisylvian brain anatomy of musicians vary as a function of the particular measurement methodology being used (VBM vs. measurement of cortical thickness [CT]). These studies provide strong evidence that CV is confounded by the incompatibility of thickness and surface.

Cortical surface area (CSA) has increased enormously during the evolution of primates, while the thickness of the cortex has remained relatively constant. According to the radial unit hypothesis (Rakic 1988, 1995), the amount of CSA possessed by a distinct area is driven by the number of columns; CT is influenced by the number and the size of cells within a column, packing density, as well as by the number of connections and the extent of their myelination (Rakic 1988; Eickhoff et al. 2005). Hence, we consider CT and CSA as neuroanatomical traits, which must be measured separately, when investigating the neuroarchitecture of the human cortex and its asymmetry.

After considering the aforementioned issues, we decided to perform an MRI study that measures GM architecture in an ensemble of anatomically confined and distinct bilateral auditory-related regions in 104 human brains. For this purpose, we decided to apply an automated surface-based morphometric measurement with the FreeSurfer software (Dale et al. 1999; Fischl, Sereno, Dale 1999), which has several advantages over VBM measurements. First, it allows the separate analysis of CT, CSA, and CV. Secondly, it provides a complete set of predefined anatomical regions that guarantee precise anatomical assignment of results. Thirdly, the algorithm implemented in FreeSurfer allows a finer spatial accuracy at the subvoxel level. Furthermore, it has been shown that the SPM-based (Statistical Parametric Mapping, www.fil.ion.ucl.ac.uk/spm/) VBM approach falls victim to noise and mis-segmentation of GM, WM, and cerebrospinal fluid and is significantly affected by partial volume effects (Clarkson et al. 2011). By means of FreeSufer analysis technique, a recent study has identified regional CV asymmetries between the 2 hemispheres (Goldberg et al. 2013). As our particular interest targets the investigation of structural asymmetries in the auditory-related cortex, we selected 5 distinct regions of the auditory-related cortex. Akin to a former study by Sigalovsky et al. (2006) who used the MR-based longitudinal relaxation rate (R1) to elaborate on myelin content of selected distinct auditory core and auditory association areas, we collected CV, CT, and CSA values from an ensemble of auditory-related regions, namely the HG, HS, lateral STG, PT, and PP. The following description of the aforementioned selected regions' anatomical positions and borders are partly taken from Destrieux et al. (2010, pp. 8–9).

HG or the transverse temporal gyrus accommodates the primary auditory cortex (Penhune et al. 1996; Morosan et al. 2001; Rademacher et al. 2001; Leonard et al. 2008). "It is a small swelling containing primary auditory cortex, just anterior and parallel to the transverse temporal sulcus" (Destrieux et al. 2010, p. 8). The initial level of the cortical processing of spoken language traverses here, before entering the next step involved in the hierarchical speech processing stream (Hickok and Poeppel 2007). A leftward volume asymmetry of the HG has been previously introduced by Schneider et al. (2002) and Takao et al. (2011).

HS or otherwise known as the transverse temporal sulcus "is an important landmark at the superior aspect of the temporal lobe since it divides the PT (posteriorly) from the transverse temporal gyrus (anteriorly); it originates at the posterior segment of the lateral sulcus, runs anterior and lateral, and joins the lateral aspect of the temporal lobe" (Destrieux et al. 2010, p. 8). The PT adjoins the formation of the HG/HS caudally (Westbury et al. 1999).

"The PT is the part of the superior aspect of the STG, posterior to the transverse temporal sulcus" (Destrieux et al. 2010, p. 8). It mediates auditory and elemental speech processing (Jancke et al. 2002; Zaehle et al. 2004; Price 2012) and has hence been dubbed the major "computational hub" for spectro-temporal analysis of acoustic signals (Griffiths and Warren 2002). Numerous studies have shown leftward volume and size asymmetry of the PT in humans (Geschwind et al. 1968; Chance et al. 2006; Dorsaint-Pierre et al. 2006; Takao et al. 2011) and in apes (Gannon et al. 1998).

The PP "is the part of the superior aspect of the STG located anterior to the transverse temporal gyrus. This flat area reaches the temporal pole anteriorly, and the parahippocampal gyrus medially" (Destrieux et al. 2010, p. 8). Little is known about the particular function of the PP so far. Several neuroimaging studies that explicitly used auditory tasks report responses of the PP bilaterally (Meyer et al. 2000; Patterson et al. 2002; Warren et al. 2003; Brown et al. 2004; Baumann et al. 2007). To the best of our knowledge, data about volume, thickness, and surface area asymmetry of this cortical area in human brains have yet to be published.

The STG (or T1) "constitutes the temporal operculum and faces the frontal and parietal opercula. Its medial limits are: The inferior segment of the circular sulcus of the insula (anteromedially) and the posterior segment of the lateral sulcus (posteromedially). Its lateral limit was drawn on the "pial" view at the junction between the lateral and superior aspects of the STG" (Destrieux et al. 2010, p. 8). Here, our anatomical analysis focused on the lateral aspect of the STG, which "is the only part of the STG visible on the "pial" view and is connected posteriorly to the inferior parietal lobule" (Destrieux

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et al. 2010, p. 9). The bilateral STG is recruited during nonprimary auditory processing of speech and nonspeech sounds (Binder et al. 2000; Meyer, Zysset, et al. 2005; Zaehle et al. 2008). A leftward asymmetry of GM myelination in the STG has been reported by Sigalovsky et al. (2006).

Even though the above-mentioned findings of leftward asymmetry in auditory-related cortical regions appear to paint a consistent picture, the relationship between adjacent auditory-related cortical regions has not yet been systematically investigated. Thus, we present an investigation of the different aspects of GM architecture asymmetry (CV, CT, and CSA) in 5 auditory-related regions, as well as their interdependence on one another. Previous studies claim that CV is a less appropriate parameter, for example, Panizzon et al. (2009, p. 2732) state, "measurements of GM volume conflate the contributions of thickness and surface area and therefore, may not capture the basic structural elements of the cerebral cortex." Indeed, a study by Winkler et al. (2010, p. 1141) underlines that volume is strongly correlated with surface area and concludes "… that GM volume, which is a composite of 2 other traits (surface area and thickness), might not be the best choice." Thus, we predict that we will find an independent relationship between CSA and CT. In addition, we expect that CSA will strongly predict CV. Furthermore, in agreement with foregoing functional studies, we expect to find leftward asymmetric measurements in the CSA dedicated to speech-related auditory structures (Meyer, Zaehle, et al. 2005, Meyer, Zysset, et al. 2005), such as the PT (Jancke et al. 2002). We make these predictions because the amount of CSA is influenced by the number and spacing of neuronal columns. As indicated by Galuske et al. (2000) and Rosen (1998), the spacing between columns as well as the sheer number of neurons account for the leftward asymmetry of posterior temporal regions. The leftward functional dominance of speech functions should be reflected by a structural substrate, namely the extension of distinct cortical portions. Furthermore, we expect to find an asymmetric relationship between the left and right CT. It is conceivable that the asymmetry index (AI) for CT could demonstrate a rightward asymmetry, because the speech-related areas in the left superior temporal region might be thinner due to stronger myelineation (Sigalovsky et al. 2006; Sowell et al. 2007).

To contribute to the ongoing discussion about the existence of sex differences in hemispheric asymmetry (Luders et al. 2004, 2009; Im et al. 2006; Sowell et al. 2007; Leonard et al. 2008; Ihnen et al. 2009), we collected brain scans from a sufficiently large sample of male and female individuals. This enables us to run comprehensive and robust analyses, in order to test putative sex-related differences. Although some computational neuroanatomy studies report differences in global and local perisylvian neuroarchitecture that varies as a function of sex (Im et al. 2006; Sowell et al. 2007), we do not anticipate discovering differences in asymmetry measurements, as we maintain that cortical asymmetry has evolved equally in men and women for the sake of lateralized auditory functions.

Materials and methods

Participants

Fifty-two women with a mean age of 26.2 years (SD: 8.0 years) and 52 men who were matched for both age (28.3 ± 7.1 years) and handedness participated in this study. Given that most of the participants in both groups had attended university, their years of education were closely matched. According to the Annett handedness inventory (Annett 1970), all participants were consistently right-handed. All participants declared that they had no history of neurological, neuropsychological, or psychiatric disease, and that they did not use drugs or take medication. Each volunteer gave informed written consent. The local ethics committee (SPUK, Medical School, University Hospital of Zurich) approved this study.

MRI Data Acquisition

MRI scans were acquired using a 3.0-T Philips Intera whole-body scanner (Philips Medical Systems, Best, The Netherlands), which is equipped with a transmit-receive body coil and a commercial 8-element sensitivity-encoding (SENSE) head coil array. A volumetric 3-dimensional (3D) T_1-weighted gradient-echo sequence (turbo field echo) scan with a spatial resolution of $0.86 \times 0.86 \times 0.75$ mm (matrix 256×256 pixels, 180 slices) was conducted for each of the 104 participants. Further imaging parameters were: Field of view = 220×220 mm, echo time = 2.3 ms, repetition time = 20 ms, flip angle (α) = 20°.

Surface-Based Morphometry

The reconstruction of cortical surface and volumetric segmentation were performed with the FreeSurfer image analysis suite (version 4.1.0). This software is documented online and is available for download free of charge (http://surfer.nmr.mgh.harvard.edu/). The technical details of these procedures are described in prior publications (Dale et al. 1999; Fischl, Sereno, Dale 1999; Fischl, Sereno, Tootell, et al. 1999; Fischl et al. 2001, 2002; Fischl, Salat, et al. 2004). Briefly, the 3D structural T_1-weighted MRI scan was used to construct models of each volunteer's cortical surface in order to measure brain anatomy traits, such as CT, CSA, and CV. This is a fully automated procedure that involves segmentation of the cortical WM (Dale et al. 1999), tessellation of the GM/WM junction, inflation of the folded surface tessellation patterns (Fischl, Sereno, Dale 1999), and automatic correction of topological defects in the resulting manifold (Fischl et al. 2001). This surface is then utilized as the starting point for a deformable surface algorithm that is designed to find the gray/white and pial (GM/cerebrospinal fluid) surfaces with submillimeter precision (Fischl and Dale 2000). The procedures for measuring CT have been validated against histological analysis (Rosas et al. 2002) and manual measurements (Kuperberg et al. 2003; Salat et al. 2004). This method uses both intensity and continuity information from the surfaces in the deformation procedure in order to interpolate surface locations for regions in which the MRI image is ambiguous (Fischl and Dale 2000). For each participant, CSA and CT of the cortical ribbon were computed on a uniform grid (comprised by vertices). CT is defined by the shortest distance between the gray/white and pial surface models. The thickness maps produced are not limited to the voxel resolution of the image and are thus sensitive to submillimeter differences between any groups at issue (Fischl and Dale 2000). Thickness, surface area, and volume measures were mapped to the inflated surface of each participant's brain reconstruction, thus allowing the visualization of data across the entire cortical surface (i.e. gyri and sulci) without the data being obscured by cortical folding. Each participant's reconstructed brain was then morphed to an average spherical surface representation that optimally aligned sulcal and gyral features across participants (Fischl, Sereno, Tootell, et al. 1999). This procedure provides accurate matching of morphologically homologous cortical locations among participants on the basis of each individual's anatomy, while nevertheless minimizing metric distortions.

The cerebral cortex was parcellated into units based on the gyral and sulcal structure (Fischl, van der Kouwe, et al. 2004; Desikan et al. 2006; Destrieux et al. 2010) and a variety of surface-based data, including maps of CV, CT, and CSA, were created.

Cortical Parcellation of Auditory-Related Brain Areas

One of FreeSurfer's implemented parcellation schemes (aparc.a2005s) was used to compute total CT, total CSA, and total CV in 154

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anatomical structures across both cortical hemispheres (Destrieux et al. 2010). From these 154 anatomical structures, the following auditory-related brain regions were selected: HG, HS, PT, PP, and the lateral aspect of STG (Fig. 1).

Statistical Analysis

Statistical analyses were performed to test for global sex-related differences, as well as both global and local patterns of neuroanatomical asymmetry for the pooled sample. First, we compared the global architectonic measures of women with those of men by using analysis of covariance models with total intracranial volume as covariates of no interest. Secondly, we tested for sex-related differences in asymmetry in whole-brain measurements. Thirdly, we calculated differences between the left and right measurements of global CV, CT, and CSA for the total sample. Fourthly, for each neuroanatomical trait, we compared architectonic measures of the left hemispheric structure with those of the right hemispheric homolog using paired *t*-tests for each individual ROI. Furthermore, an AI according to the formula AI = (left − right)/(left + right) was calculated for each ROI and for each trait. After which we applied 1-sample *t*-tests against zero to test for significant asymmetry. To explore the relationship between the regions and the traits, we utilized a comprehensive correlation analysis. Accordingly, we correlated the AI between all ROIs for each trait individually. Finally, we separately analyzed the correlation of AIs between all traits for each region. Where appropriate, the Bonferroni procedure was applied in order to correct error probability for multiple comparisons.

Results

Age and global brain anatomy traits are summarized in Table 1. There is no statistically significant age difference between women and men ($P = 0.21$). The results portray several differences between male and female brains in global neuroanatomical parameters. In particular, male brains demonstrate a larger global surface area in both the left and right hemispheres. However, according to our predictions, we found no global significant differences of structural asymmetry between male and female brains (cf. Table 2). Thus, we proceeded with statistical analyses based on local indices of asymmetry that are pooled across participants' sex.

Table 3 summarizes the global measurement of cortical parameters for the pooled sample. The table displays the calculations of hemispheric measurements of CV, CT, and CSA. We also tested for differences between the left and right hemisphere and consequently observed a significant (Bonferroni corrected) leftward asymmetry for total CV ($P << 0.0001$) and a rightward asymmetry for total CSA ($P << 0.0001$).

With respect to selected regions of the auditory-related cortex, we noted CSA, which was pooled across sex, to be increased in the left (compared with the right) HG, HS, PT, and STG. No significant asymmetry is noted for the PP. Analysis of CT traits reveals a significant rightward asymmetry for HG and HS and a leftward asymmetry for PP. Akin to surface area measurement, the calculation of CV results in leftward asymmetry for HG, PT, and STG (cf. Table 4). These findings indicate that CT and CSA should actually be considered as independent traits (Fig. 2).

Furthermore, we assessed whether the asymmetry of a region depends on the asymmetry of its neighboring regions (cf. Table 5) and performed correlation analyses of AI between all 5 regions. With respect to thickness and volume, STG and PT are significantly lateralized towards the left. No correlations between adjoining regions were found for CSA.

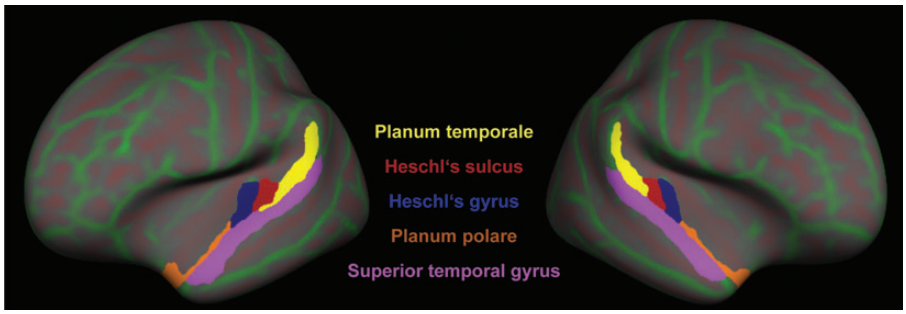

Figure 1. Parcellation scheme of 5 selected auditory-related brain areas projected onto the inflated surface of FreeSurfer's average template (rotated by 50°, to enable a better view on the supratemporal plane).

Table 1

Demographic data and global neuroanatomical traits are presented separately for male ($N = 52$) and female ($N = 52$) participants

Measure	Females ($N = 52$)				Left–right	Males ($N = 52$)				Left–right	Males–Females
	Mean	SD	Minimum	Maximum	*P*-value	Mean	SD	Minimum	Maximum	*P*-value	*P*-value
Age (years)	26.2	8.0	16.0	59.0	–	28.3	7.1	18.0	48.0	–	0.21
Intracranial volume (cm^3)	1480.9	158.6	1158.3	1832.7	–	1610.5	146.8	1320.0	1968.3	–	**3.6E−05**
Left cerebral WM volume (cm^3)	197.0	26.5	151.0	270.0	0.33	241.8	32.7	170.8	324.1	0.91	**4.0E−08**
Right cerebral WM volume (cm^3)	196.3	27.4	147.6	272.6	–	241.7	32.7	169.7	322.3	–	**4.5E−08**
Left cortical volume (cm^3)	246.3	23.2	189.9	294.9	**3.1E−05**	269.4	27.6	208.2	318.4	**0.020**	0.058
Right cortical volume (cm^3)	239.9	22.2	192.4	292.7	–	266.3	27.6	209.0	322.1	–	**0.004**
Mean left cortical thickness (mm)	2.706	0.101	2.342	2.892	0.35	2.637	0.132	2.304	2.900	0.89	**4.7E−04**
Mean right cortical thickness (mm)	2.696	0.090	2.519	2.922	–	2.636	0.129	2.322	2.903	–	**0.002**
Left cortical surface area (cm^2)	888.8	77.5	728.0	1053.7	**0.001**	1010.8	86.2	838.4	1199.1	**6.5E−14**	**2.6E−08**
Right cortical surface area (cm^2)	905.1	75.6	740.0	1066.5	–	1038.8	89.3	855.1	1238.1	–	**5.3E−10**

P-values in bold indicate statistical significance ($P < 0.05$).

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Table 6 depicts results produced by a correlation analysis of AIs between measurements for distinct ROIs. These calculations resulted in significant correlations between CT and CV in 4 of 5 ROIs (HG, HS, PT, and STG). Significant correlation values between CSA and CV are observed for all 5 ROIs. No significant correlations between CSA and CT were found. In 3 of 5 regions (HG, HS, and PP), we found a negative relationship between CT and CSA. Even though the correlation is not significant after applying a correction, we note that the uncorrected *P*-value of the negative correlation between CT and CS for the HS and PP is actually $P < 0.05$. This pattern functions as additional evidence that CT and CSA are negatively related or are at least independent traits.

Table 2
Global AIs of brain anatomy traits, namely CV, CT, and CSA, are presented separately for male ($N = 52$) and female ($N = 52$) participants

Measure	Females ($N = 52$)		Males ($N = 52$)		Males–Females
	Mean	SD	Mean	SD	*P*-value
AI cortical volume	0.013	0.020	0.006	0.018	0.063
AI cortical thickness	0.002	0.014	0.000	0.014	0.588
AI cortical surface area	−0.009	0.017	−0.014	0.010	0.114

Table 3
Demographic data and global neuroanatomical traits are pooled across all participants ($N = 104$), irrespective of sex.

Measure	Pooled sample ($N = 104$)				Left–right
	Mean	SD	Minimum	Maximum	*P*-value
Age (years)	27.1	7.4	16.0	59.0	–
Intracranial volume (cm^3)	1545.7	165.5	1158.3	1968.3	–
Left cerebral WM volume (cm^3)	219.4	37.2	151.0	324.1	0.49
Right cerebral WM volume (cm^3)	219.0	37.7	147.6	322.3	–
Left cortical volume (cm^3)	257.9	27.9	189.9	318.4	**3.2E−06**
Right cortical volume (cm^3)	253.1	28.2	192.4	322.1	–
Mean left cortical thickness (mm)	2.671	0.122	2.304	2.900	0.44
Mean right cortical thickness (mm)	2.666	0.115	2.322	2.922	–
Left cortical surface area (cm^2)	949.8	102.0	728.0	1199.1	**2.7E−13**
Right cortical surface area (cm^2)	972.0	106.3	740.0	1238.1	–

P-values in bold indicate statistical significance ($P < 0.05$).

Discussion

Based on an automated surface-based morphometry approach (Dale et al. 1999; Fischl et al. 2002), the present study delineates local asymmetries of CV, CT, and CSA in 5 auditory-related perisylvian regions, namely HG, HS, PT, PP, and lateral STG. This study consists of 3 goals. First of which is to provide a comprehensive description of structural asymmetries of auditory-related cortical regions. Second of which is to critically discuss the empirical validity of how CV is both measured and interpreted as an appropriate neuroanatomical trait for investigating morphological brain asymmetry. The third goal is to contribute to the ongoing discussion about sex-related differences in the auditory-related regions that are crucially involved in speech processing. Relating the present findings of local structural asymmetries to potential functional differences between the left and right auditory-related cortical regions would be interesting; however, the question remains as to whether cognitive and sensory processes should indeed be mapped onto macroanatomy. Recent publications have demonstrated that higher-level cognitive processes, when compared with lower-level sensory functions, such as auditory perception, are less reliably linked to macroanatomically distinct and confined cortical regions (Frost and Goebel 2012; Tahmasebi et al. 2012). Since the data regarding structural asymmetries do not provide a solid foundation for the discussion of potential relationships between speech functions and specific findings of asymmetries in thickness and surface area, we will refrain from speculating about a relationship between this work's results and the functional architecture of language.

Most importantly, our analyses demonstrate a consistent and reliable pattern of the relationships between CT, CSA, and

Table 4
Mean values for neuroanatomical traits in the left and right auditory-related cortical regions

	Pooled sample ($N = 104$)				*P*-value	Effect size	AI
	Left hemisphere		Right hemisphere				>0 = left
	Mean	SD	Mean	SD			<0 = right
Cortical volume (mm^3)							
Heschl's gyrus	1105	266	872	220	**8.1E−16**	0.947	0.12
Heschl's sulcus	532	120	498	130	0.029	0.218	0.04
Planum temporale	2157	601	1797	525	**6.2E−08**	0.575	0.09
Planum polare	1624	403	1627	448	0.95	−0.006	0.002
Superior temporal gyrus	6616	1323	5693	1025	**7.0E−14**	0.876	0.07
Cortical thickness (mm)							
Heschl's gyrus	2.43	0.28	2.53	0.29	**3.7E−04**	0.361	−0.02
Heschl's sulcus	2.56	0.33	2.94	0.37	**5.7E−15**	−0.899	−0.07
Planum temporale	2.74	0.22	2.76	0.27	0.35	−0.092	−0.004
Planum polare	3.48	0.41	3.26	0.37	**5.2E−09**	0.628	0.03
Superior temporal gyrus	3.27	0.22	3.21	0.28	0.018	0.242	0.01
Cortical surface area (mm^2)							
Heschl's gyrus	452	95	344	76	**1.3E−21**	1.211	0.14
Heschl's sulcus	209	48	171	46	**4.8E−10**	0.675	0.10
Planum temporale	780	212	649	173	**1.5E−08**	0.609	0.09
Planum polare	467	107	497	121	0.028	−0.219	−0.03
Superior temporal gyrus	1983	352	1728	262	**4.4E−15**	0.941	0.07

Note: The table shows results of paired *t*-tests, effect sizes, and AI for the comparison between mean values. Results are corrected for multiple comparisons (nominal $P = 0.05$, Bonferroni corrected $P = 0.05/5 = 0.01$).
P-values in bold indicate statistical significance ($P < 0.05$).

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CV. We observed that mean values of CSA and CT asymmetry in auditory-related regions are independent, while both CT and CSA asymmetry partially correlate with CV measurements. These findings pose serious implications for the reevaluation of previous morphological studies, which based their interpretations on CV—a combined measurement of CT and CSA. In the following discussion, we start by exploring this issue in light of our findings related to structural asymmetries in auditory-related areas. Subsequently, we discuss local asymmetries and their potential implications for functional lateralization.

Global Asymmetries

To evaluate the impact of global measurements on local asymmetries, we compared global CV, CT, and CSA measurements between the left and right hemisphere. The sole significant differences are found for CV (leftward asymmetry) and CSA (rightward asymmetry). We shall refrain from interpreting the global leftward asymmetry in CV as our paper outlines why it is disadvantageous to interpret CV, when compared with CT and CSA. Our findings of global rightward CSA asymmetry conflict with the observation of local leftward CSA asymmetry in auditory-related cortical regions. Hence, we do not argue that our results regarding local asymmetry are biased by global patterns in asymmetry.

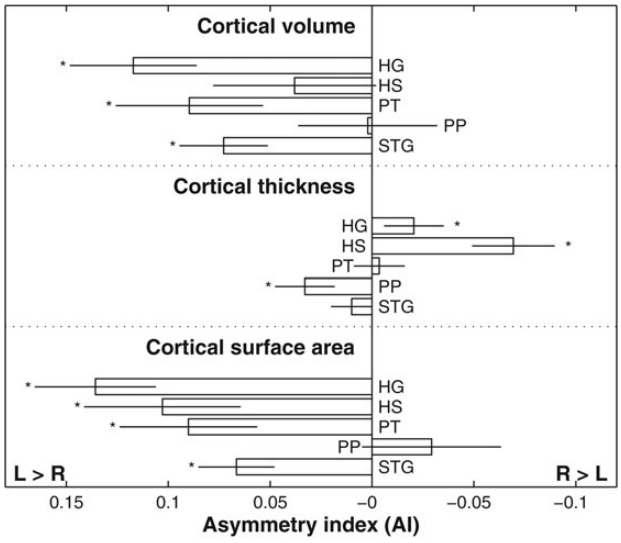

Figure 2. Schematic illustration of AIs for neuroanatomical traits, namely CV, CT, and CSA (horizontal lines indicate the 95% confidence interval; asterisks denote a significant asymmetry at $P < 0.05$).

Relationship Between CV, CT, and CSA

How neuroanatomical traits are frequently used in present computational neuroanatomy is a critical issue. While the analysis of CV has long been viewed as the "gold-standard" in computational neuroanatomy, recent publications suggest an alternative approach. As apparent from Table 6, CSA and CV show a significant positive correlation, whereas the correlation between CT and CV is statistically less prominent suggesting a complex relationship between these traits; this pattern of results challenges the present understanding of CV as an ideal marker. One may wonder how the relationship between CSA and CT can be described. Intuitively, one would assume that CSA and CT might run into opposite directions. A larger surface might function to house a greater number of WM afferents, but this could be at the expense of CT. Indirect evidence for this view was provided by a postmortem study that measured a greater posterior superior temporal lobe WM volume in the left compared with the right hemisphere (Anderson et al. 1999). An additional postmortem study reported a thinner and longer cortex in the left PT with the contralateral area demonstrating a shorter and thicker cortex (Harasty et al. 2003). Differential developmental lines may explain this difference because in order to house the greater volume of regional WM the left PT expands tangentially in volume and becomes both larger in area and thinner. According to Harasty et al. (2003, p. 257), these particular differences between left and right auditory-related cortex architecture may have functional implications: "in this case specific to speech perception." Because of the larger stretching of neuronal columns in the left PT, they are more widely spaced apart; this might correspond to a better differentiation of

Table 5
Results of correlation analyses between adjacent regions for differential neuroanatomical traits

	Heschl's gyrus	*P*-value	Heschl's sulcus	*P*-value	Planum temporale	*P*-value	Planum polare	*P*-value
Cortical volume								
Heschl's gyrus								
Heschl's sulcus	−0.059	0.553						
Planum temporale	0.05	0.611	−0.121	0.219				
Planum polare	0.042	0.671	−0.022	0.824	0.174	0.077		
Superior temporal gyrus	0.037	0.713	0.09	0.362	**0.330**	**0.001**	0.165	0.093
Cortical thickness								
Heschl's gyrus								
Heschl's sulcus	0.217	0.027						
Planum temporale	0.088	0.375	0.131	0.183				
Planum polare	−0.113	0.255	0.145	0.143	0.009	0.932		
Superior temporal gyrus	−0.097	0.329	−0.18	0.067	**0.303**	**0.002**	−0.034	0.732
Cortical surface area								
Heschl's gyrus								
Heschl's sulcus	0.117	0.239						
Planum temporale	0.103	0.298	0.023	0.819				
Planum polare	0.089	0.37	−0.006	0.953	0.183	0.062		
Superior temporal gyrus	−0.015	0.882	0.196	0.046	0.222	0.024	0.097	0.327

Note: Results are corrected for multiple comparisons (nominal $P = 0.05$, Bonferroni corrected $P = 0.05/5 = 0.01$).
P-values in bold indicate statistical significance ($P < 0.05$).

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Table 6
Results of correlation analyses between differential neuroanatomical traits for 5 superior temporal regions are presented separately

	CV × CT	*P*-value	CT × CSA	*P*-value	CV × CSA	*P*-value
Heschl's gyrus	**0.313**	**0.001**	−0.135	0.173	**0.895**	**1E−37**
Heschl's sulcus	**0.293**	**0.003**	−0.199	0.043	**0.876**	**4E−34**
Planum temporale	**0.372**	**1E−4**	0.065	0.515	**0.947**	**3E−52**
Planum polare	0.164	0.097	−0.205	0.037	**0.928**	**2E−45**
Superior temporal gyrus	**0.448**	**2E−6**	0.036	0.716	**0.904**	**2E−39**

Note: Results are corrected for multiple comparisons (nominal $P = 0.05$, Bonferroni corrected $P = 0.05/10 = 0.005$).
P-values in bold indicate statistical significance ($P < 0.05$).

incoming signals. Columns found on the right auditory-related cortex may act together in sets under some circumstances because their functional units exhibit reduced spacing (Harasty et al. 2003). This result holds for the PT only and needs verification for a larger number of auditory-related regions. Other neuroimaging studies also noticed that mean values of thickness and surface area are independent, which indirectly supports the findings of Harasty and colleagues (Panizzon et al. 2009). In addition, Hogstrom et al. (2012, p. 1) reason that "regional increases in surface area during the ontogeny may be driven or facilitated by plastic processes inducing cortical thinning, suggesting regional negative correlations between area and thickness originating from early childhood." In their study, significant negative relationships between CT and CSA were found in several brain regions, but were absent in the auditory-related regions. This observation concurs with our pattern of results. Similarly, Winkler et al. (2010) examined the relationship between CSA and CT in a number of predefined regions in the adult human brain and reported only weak or a total absence of correlations between these 2 structural neuromarkers. They thereby concluded: "surface area and CT measurements should be considered separately" (p. 1135). Thus, CSA "is distinct from CT in its contribution in volume" (Eyler et al. 2011, p. 2313). Our results are in line with previous observations, which consider CV as a less ideal marker for anatomical measurements, because it is the product of 2 independent factors.

Neuroanatomical Relationship Between Auditory-Related Regions

Another of our a priori assumptions pertained to the direct relationship between anatomical asymmetry and cortical regions that reside beside one another. It is plausible that neighboring regions of the auditory-related cortex demonstrate the same patterns of asymmetry, as is portrayed in Table 5, in the form of a correlation between the neighboring regions of PT and the lateral STG, and the traits CT and CV. It is not surprising that directly adjoining cortical areas demonstrate equivalent patterns of morphological asymmetry. However, this result is not compelling and systematic evidence for our initial assumption. Perhaps, the reasoning about the similar pattern of cortical architecture occurring in auditory-related areas should be abandoned.

Theoretical Embedding of Present Results

According to our data, CSA and CT should be considered independent neuroanatomical traits that are likely to be influenced by different factors during brain development (Frye et al. 2010). In agreement with this view, Panizzon et al. (2009) propose that CSA and CT have different origins. While CSA increases during late fetal development due to cortical folding, CT alters dynamically across the entire life span as a consequence of training, experience, and disease. A comprehensive explanation for the independent status of CSA and CT is provided by the "radial unit hypothesis" (Rakic 1988, 2000), which considers the cortical column as a fundamental unit of cortical architecture. All cells within a vertical column have a common origin and migrate to their final destination during prenatal development (Rakic 1995). The radial unit hypothesis further postulates that the size of CSA is determined by the number of vertical columns, whereas the CT is driven by the number of neurons within each column. Thus, the radial unit hypothesis also outlines why the human cerebral cortex has expanded that much more immensely during phylogeny than size of the cortical sheet in other animals (Rakic 2009). During evolution, there has been an "expansion of cortical surface without the expansion of cortical width" (Rakic 2007, p. 213). Not only phylogeny plays a role, "ontogenetic increases in CV are largely driven by increasing gyrification and associated surface area expansion rather than increased CT" (Hogstrom et al. 2012, p. 1). In more detail, Rakic (2007, p. 214) describes the independent development of CSA and CT: "The increase in the number of founder cells lead to larger number of radial columns (…). In contrast, over-expression of cyclin-dependent kinase (cdk) inhibitor, p27, increases the production of neurons that form radial columns, thus increasing the thickness of the superficial layers of the cortex, without increasing its surface area." Taken together, the radial unit hypothesis provides a reasonable framework, which buttresses our conclusion that there is an independent relationship between CSA and CT in the auditory-related cortex.

Our finding of larger CSA and thinner CT in the left auditory-related fields, as well as results from other volumetric studies can be aligned with recent microscopic findings. According to Chance et al. (2006, p. 1041), the asymmetry of CSA in the posterior supratemporal plane "is a function of minicolumn spacing" in that "minicolumn spacing and minicolumn number were greater" in the left auditory-related regions. Along these lines, Hutsler and Galuske (2003, p. 433) propose that wider spacing between neuronal microcolumns could be an "important advantage of the left hemisphere for extracting crucial temporal information from the incoming stream of auditory inputs and, thus, analyzing these inputs under different conditions than the right hemisphere." More specifically, larger CSA of posterior auditory-related areas in the left hemisphere "may be related to the temporal demands of auditory processing" (Hutsler and Galuske 2003, p. 238). The lateralized processing of auditory cues that comprised different temporal duration and spectral complexity evident in an array of functional imaging studies are interpreted as being a function of the structural microanatomical asymmetry of auditory-related cortical areas (Zatorre and Belin 2001; Jamison et al. 2006).

Apparently, apes and monkeys do not show this microscopic difference (Buxhoeveden et al. 2001), which may implicate a particular involvement of these regions in speech processing. Supporting evidence comes from data demonstrating interhemispheric differences in the microcircuitry architecture of the posterior portion of the STG (Galuske et al. 2000; Hutsler and Galuske 2003). These differences are

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present in the form of neuronal clusters that are more widely spaced in the left STG and which exhibit subsystems that are 30% more distinct within the same volume of tissue, compared with the contralateral area. According to Galuske et al. (2000, p. 1949), "these subsystems are tuned to different features (…)." Analogous to the visual cortex, "more feature domains could be represented in the left than in the right area 22 without reduction in the number of neurons devoted to a particular feature. This, then, is likely to permit a more fine-grained analysis of feature domains, and we propose that this is related to special functions of auditory processing such as are required, e.g. for the analysis of speech." First, neuronal columns, which are spaced more widely apart, can process over-learned phonetic patterns that are extracted from the inflowing speech signal more efficiently and automatically, since this specific architecture is proficient at storing and recognizing frequent spectro-temporal acoustic patterns. Secondly, larger number of columns in the left HG and PT as observed by Chance et al. (2006) help explain the leftward CSA asymmetry exhibited by our research participants in the HG, STG, and PT regions. This leftward PT asymmetry exists at the prenatal age of 29–31 weeks (Steinmetz 1996), that is, before cortical folding is finalized (Dubois et al. 2008). This fact begs the question of whether asymmetry in the human perisylvian architecture encompasses a strong genetic disposition, and whether it is specifically designed this way, in order to enable humans to juggle acoustic speech signals comprising differential spectro-temporal complexity.

Supporting evidence for this view comes from a study that reports a leftward asymmetry of anterior and posterior perisylvian regions, which are already present in humans at 26–36 gestational weeks of age (Dubois et al. 2010).

Is a Thinner Cortex a "Better" Cortex?

In the present study, we observe a significantly thicker cortex in the right HG and HS, as well as thicker cortex in the left PP, when compared with the right hemisphere. Intuitively, one may assume that a thicker cortex is more proficient as it consists of additional GM, which may provide enhanced computational power. At first sight, this reasoning may imply that abundant computational resources are functionally advantageous. However, does this reasoning genuinely sanction the conclusion that a thick(er) cortex is a "better" cortex? Although the notions of "better" and "worse" are not helpful when one's reasoning pertains to cortical functioning, it is apparent that, under certain circumstances, a thicker cortex is associated with advantageous functioning. A structural MRI study concerning sex-related GM differences (Luders et al. 2005) consists of arguments along these lines. According to their results, numerous cortical regions demonstrate significantly stronger GM concentration in female brains compared with male brains, even when total brain size is corrected for. The authors assume that the GM increase observed in cortical areas that are associated with language functions, namely the left posterior STG and the left posterior inferior frontal gyrus, which were only demonstrated in female participants, "might be related to the improved language skills previously reported in females" (Luders et al. 2005, p. 500). However, this assumption has, as of late, been seriously called into question. Evidence offering support for an opposing view comes from a combined structural and functional MRI study that observed an inverse relationship between thickness and blood oxygen level-dependent-related responses in fronto-parietal areas during a written language task (Lu et al. 2009). Similarly, a study that combines neurophysiological measurements with structural MRI discovered that the amplitude of the auditory evoked N1 component correlates negatively with CT in the right auditory-related cortex (HS and lateral HG; Liem et al. 2012). In opposition to the view of Luders et al. (2005), the authors of the EEG and structural MRI paper suggest that a thinner cortex might correspond to a slender yet efficient neural organization that is formed postnatally as a function of learning-dependent plasticity.

Albeit the absence of functional data in our study, this controversial issue should nevertheless be briefly addressed in the context of our findings. The question whether "thicker" or "thinner" is better cannot be straightforwardly answered (Sowell et al. 2007). As a matter of fact, "thicker" or "thinner" can only be discussed when 2 regions, groups, or hemispheres are compared. Therefore, this question needs to be carefully embedded in the context comprising each individual study. Accordingly, Sowell et al. (2004) observed cortical thickening of 0.05–0.2 mm of GM per year in the left and right perisylvian cortices in a group of participants ranging in age from 5 to 11 years. Certainly, this thickening must be considered as a normal step in brain maturation. However, there is no doubt that this maturational cortical thickening is accompanied by the children's increasing cortical functioning. During adolescence and adulthood, a genetically driven decrease of cortical GM density can be noted (Giedd et al. 2006; Li et al. 2012; van Soelen et al. 2012). This thinning is probably attributable to increased proliferation of myelin into the periphery of the cortical neuropil and should also be considered as a normal developmental alteration. However, Sowell and colleagues emphasize that cortical thinning during this period of life "is probably not entirely caused by a reduction in the size or number of neuron cell bodies or their synaptic processes (as might be the case in normal aging)" (2004, p. 8229).

In the present study, we report differences in CT of the left and right supratemporal regions. As apparent in Table 4, the right auditory cortex is significantly thicker than the contralateral portion. In agreement with other research groups (Sowell et al. 2004; Sigalovsky et al. 2006; Brauer et al. 2010), we conjecture that an asymmetric increase of WM volume, that is, increased myelination during cortical maturation in the left auditory cortex may account for this difference since GM has been replaced by WM, in order to establish denser connections between primary and secondary auditory regions and posterior Sylvian speech-related areas. Still, this presumption remains vague without comprehensive analysis of CT and CSA in combination with complementary WM measurements. Based on the present data, we cannot conclude whether a "thinner" or a "thicker" auditory cortex can be considered "better."

Sex-Related Differences

Putative differences in neuroanatomical indications that may vary as a function of biological sex have been a matter of several investigations. While there is some evidence that male and female human brains differ in global cortical complexity (Luders et al. 2004, 2006, 2009) and global CV (Lv et al. 2010; Takahashi et al. 2011), serious problems arise when one

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wishes to draw conclusions about alleged intersex differences in single distinct regions. According to Leonard et al. (2008), the influence of individual differences in brain volume is underestimated and may account for the observed sexual dimorphism. With respect to the perisylvian cortex, an alternative explanation may be provided by the observations of Toro and colleagues. They report that larger human brains have disproportionally more surface area than smaller brains, irrespective of biological sex (Toro et al. 2008). In other words, this bias may play a role when researchers compare male brains with female brains, in that, the surface area of male brains is assessed as being larger. Corroborating evidence for this point of view comes from a study, which showed that the cortical geometry of a larger brain is not simply a scaled-up version of a small brain (Im et al. 2008), but that in larger brains the increase of cortical GM surface area is driven by increased sulcal convolution.

While some recent computational neuroanatomy studies have not observed sex-related GM differences in auditory-related regions (Tamnes et al. 2010; Takao et al. 2011), other studies provide empirical support for the notion of sex-related differences in local language-related portions of the brain. For example, Im et al. (2006) evidenced greater CT in female brains in bilateral caudal STG. Sowell et al. (2007) observed more pronounced thickness in female brains at both temporal and parietal sites, irrespective of age and body size. However, none of these studies thoroughly investigated the measurements of asymmetry between male and female brains in the auditory cortex. Keeping this in mind, we are inclined to conclude that sexual dimorphism should not be considered as a key and should be regarded as an ignorable variable in the context of our study.

Limitations

An investigation that only focuses on asymmetries in GM architecture is not complete. Of course, it would have been beneficial to additionally quantify potential asymmetries of WM fiber tracts, in order to achieve a comprehensive picture of the local relationship between GM and WM measurements. WM primarily consists of myelinated axonal fibers and undoubtedly plays an essential role in the integration of inflowing and outflowing information between distinct anterior and posterior auditory-related areas (Sigalovsky et al. 2006; Barrick et al. 2007; Makris and Pandya 2009). One study that mapped and evaluated both cortical development and WM maturation reports a negative correlation between WM volume and CT in 24 of 33 investigated regions (Tamnes et al. 2010). This result may complement our data as it suggests that asymmetric prominence of WM fibers in left (or right) supratemporal regions may come at the expense of CT.

Conclusions

In summary, our present approach provides evidence for structural asymmetries of several distinct auditory-related regions in the human brain. CSA measurements indicate a strong leftward asymmetry in 4 of the 5 selected regions. This result obviously reflects the existence of a larger number of cortical columns, which might be more widely spaced apart. This neural pattern may be related to the supremacy of the left auditory-related region for decoding rapid acoustic modulations during speech perception. A rightward asymmetry could be observed for CT in only the primary and secondary auditory cortex. Generally, our finding points to an independent relationship between these 2 anatomical markers. Based on our results, we suggest that CV might be considered as a less suitable indicator for anatomical asymmetries since this variable is a product of CSA by CT.

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Notes

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References

Anderson B, Southern BD, Powers RE. 1999. Anatomic asymmetries of the posterior superior temporal lobes: a postmortem study. Neuropsychiatry Neuropsychol Behav Neurol. 12:247–254.

Annett M. 1970. A classification of hand preference by association analysis. Br J Psychol. 61:303–321.

Ashburner J, Friston KJ. 2000. Voxel-based morphometry—the methods. Neuroimage. 11:805–821.

Barrick TR, Lawes IN, Mackay CE, Clark CA. 2007. White matter pathway asymmetry underlies functional lateralization. Cereb Cortex. 17:591–598.

Baumann S, Koeneke S, Meyer M, Lutz K, Jancke L. 2007. A network for audio-motor coordination in skilled pianists and non-musicians. Brain Res. 1161:65–78.

Beaton AA. 1997. The relation of planum temporale asymmetry and morphology of the corpus callosum to handedness, gender, and dyslexia: a review of the evidence. Brain Lang. 60:255–322.

Bermudez P, Lerch JP, Evans AC, Zatorre RJ. 2009. Neuroanatomical correlates of musicianship as revealed by cortical thickness and voxel-based morphometry. Cereb Cortex. 19:1583–1596.

Binder JR, Frost JA, Hammeke TA, Bellgowan PSF, Springer JA, Kaufman JN, Possing ET. 2000. Human temporal lobe activation by speech and nonspeech sounds. Cereb Cortex. 10:512–528.

Brauer J, Anwander A, Friederici AD. 2010. Neuroanatomical prerequisites for language functions in the maturing brain. Cereb Cortex. 21:459–466.

Brown S, Martinez MJ, Hodges DA, Fox PT, Parsons LM. 2004. The song system of the human brain. Brain Res Cogn Brain Res. 20:363–375.

Buxhoeveden DP, Casanova M. 2000. Comparative lateralisation patterns in the language area of human, chimpanzee, and rhesus monkey brains. Laterality. 5:315–330.

Buxhoeveden DP, Switala AE, Litaker M, Roy E, Casanova MF. 2001. Lateralization of minicolumns in human planum temporale is absent in nonhuman primate cortex. Brain Behav Evol. 57:349–358.

Chance SA, Casanova MF, Switala AE, Crow TJ. 2006. Minicolumnar structure in Heschl's gyrus and planum temporale: asymmetries in relation to sex and fiber number. Neuroscience. 143:1041–1050.

Clarkson MJ, Cardoso NJ, Ridgway GR, Modat M, Leung KK, Rohrer JD, Fox NC, Ourselin S. 2011. A comparison of voxel and surface based cortical thickness estimation methods. Neuroimage. 57:856–865.

Da Costa S, van der Zwaag W, Marques JP, Frackowiak RS, Clarke S, Saenz M. 2011. Human primary auditory cortex follows the shape of Heschl's gyrus. J Neurosci. 31:14067–14075.

Dale AM, Fischl B, Sereno MI. 1999. Cortical surface-based analysis. I: segmentation and surface reconstruction. Neuroimage. 9:179–194.

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Desai R, Liebenthal E, Possing ET, Waldron E, Binder JR. 2005. Volumetric vs. surface-based alignment for localization of auditory cortex activation. Neuroimage. 26:1019–1029.

Desikan RS, Segonne F, Fischl B, Quinn BT, Dickerson BC, Blacker D, Buckner RL, Dale AM, Maguire RP, Hyman BT et al. 2006. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. Neuroimage. 31:968–980.

Destrieux C, Fischl B, Dale A, Halgren E. 2010. Automatic parcellation of human cortical gyri and sulci using standard anatomical nomenclature. Neuroimage. 53:1–15.

Dorsaint-Pierre R, Penhune VB, Watkins KE, Neelin P, Lerch JP, Bouffard M, Zatorre RJ. 2006. Asymmetries of the planum temporale and Heschl's gyrus: relationship to language lateralization. Brain. 129:1164–1176.

Dos Santos Sequeira S, Woerner W, Walter C, Kreuder F, Lueken U, Westerhausen R, Wittling RA, Schweiger E, Wittling W. 2006. Handedness, dichotic-listening ear advantage, and gender effects on planum temporale asymmetry: a volumetric investigation using structural magnetic resonance imaging. Neuropsychologia. 44:622–636.

Dubois J, Benders M, Cachia A, Lazeyras F, Ha-Vinh Leuchter R, Sizonenko SV, Borradori-Tolsa C, Mangin JF, Huppi PS. 2008. Mapping the early cortical folding process in the preterm newborn brain. Cereb Cortex. 18:1444–1454.

Dubois J, Benders M, Lazeyras F, Borradori-Tolsa C, Ha-Vinh Leuchter R, Mangin JF, Hüppi PS. 2010. Structural asymmetries of perisylvian regions in the preterm newborn. Neuroimage. 52:32–42.

Eckert M. 2004. Neuroanatomical markers for dyslexia: a review of dyslexia structural imaging studies. Neuroscientist. 10:362–371.

Eckert MA, Leonard CM, Possing ET, Binder JR. 2006. Uncoupled leftward asymmetries for planum morphology and functional language processing. Brain Lang. 98:102–111.

Eckert MA, Lombardino LJ, Walczak AR, Bonihla L, Leonard CM, Binder JR. 2008. Manual and automated measures of superior temporal gyrus asymmetry: concordant structural predictors of verbal ability in children. Neuroimage. 41:813–822.

Eickhoff SB, Walters NB, Schleicher A, Kril J, Egan GF, Watson JDG, Amunts K. 2005. High-resolution MRI reflects myeloarchitecture and cytoarchitecture of human cerebral cortex. Hum Brain Mapp. 24:206–215.

Eyler LT, Prom-Wormley E, Panizzon MS, Kaup AR, Fennema-Notestine C, Neale MC, Jernigan TL, Fischl B, Franz CE, Lyons MJ et al. 2011. Genetic and environmental contributions to regional cortical surface area in humans: a magnetic resonance imaging twin study. Cereb Cortex. 21:2313–2321.

Fischl B, Dale AM. 2000. Measuring the thickness of the human cerebral cortex from magnetic resonance images. Proc Natl Acad Sci USA. 97:11050–11055.

Fischl B, Liu A, Dale AM. 2001. Automated manifold surgery: constructing geometrically accurate and topologically correct models of the human cerebral cortex. IEEE Trans Med Imaging. 20:70–80.

Fischl B, Salat DH, Busa E, Albert M, Dieterich M, Haselgrove C, van der Kouwe A, Killiany R, Kennedy D, Klaveness S et al. 2002. Whole brain segmentation: automated labeling of neuroanatomical structures in the human brain. Neuron. 33:341–355.

Fischl B, Salat DH, van der Kouwe AJ, Makris N, Segonne F, Quinn BT, Dale AM. 2004. Sequence-independent segmentation of magnetic resonance images. Neuroimage. 23(Suppl 1):69–84.

Fischl B, Sereno MI, Dale AM. 1999. Cortical surface-based analysis. II: inflation, flattening, and a surface-based coordinate system. Neuroimage. 9:195–207.

Fischl B, Sereno MI, Tootell RB, Dale AM. 1999. High-resolution intersubject averaging and a coordinate system for the cortical surface. Hum Brain Mapp. 8:272–284.

Fischl B, van der Kouwe A, Destrieux C, Halgren E, Segonne F, Salat DH, Busa E, Seidman LJ, Goldstein J, Kennedy D et al. 2004. Automatically parcellating the human cerebral cortex. Cereb Cortex. 14:11–22.

Foundas AL, Leonard CM, Gilmore R, Fennel E, Heilman KM. 1994. Planum temporale asymmetry and language dominance. Neuropsychologia. 32:1225–1231.

Foundas AL, Leonard CM, Hanna-Pladdy B. 2002. Variability in the anatomy of the planum temporale and posterior ascending ramus: do right- and left handers differ? Brain Lang. 83:403–424.

Foundas AL, Leonard CM, Heilman KM. 1995. Morphologic cerebral asymmetries and handedness. Arch Neurol. 52:501–508.

Frost MA, Goebel R. 2012. Measuring structural-functional correspondence: spatial variability of specialised brain regions after macroanatomical alignment. Neuroimage. 59:1369–1381.

Frye RE, Liederman J, Malmberg B, McLean J, Strickland D, Beauchamp MS. 2010. Surface area accounts for the relation of gray matter volume to reading-related skills and history of dyslexia. Cereb Cortex. 20:2625–2635.

Fullerton BC, Pandya DN. 2007. Architectonic analysis of the auditory-related areas of the superior temporal region in human brain. J Comp Neurol. 504:470–498.

Galaburda A, Sanides F, Geschwind N. 1978. Human brain. Cytoarchitectonic left-right asymmetries in the temporal speech region. Arch Neurol. 35:812–817.

Galuske RAW, Schlote W, Bratzke H, Singer W. 2000. Interhemispheric asymmetries of the modular structure in human temporal cortex. Science. 289:1946–1949.

Gannon PJ, Holloway RL, Broadfield DC, Braun AR. 1998. Asymmetry of the planum temporale: humanlike pattern of Wernicke's brain language area homolog. Science. 279:220–222.

Geschwind N, Quadfasel FA, Segarra JM. 1968. Isolation of the speech area. Neuropsychologia. 4:327–340.

Giedd JN, Blumenthal J, Jeffries NO, Castellanos FX, Liu H, Zijdenbos A, Paus T, Evans AC, Rapoport JL. 2006. Brain development during childhood and adoloscence: a longitudinal MRI study. Nat Neurosci. 2:861–5.

Goldberg E, Roediger D, Kucukboyaci NE, Carlson C, Devinsky O, Kuzniecky R, Halgren E, Thesen T. 2013. Hemispheric asymmetries of cortical volume in the human brain. Cortex. 49:200–210.

Golestani N, Molko N, Dehaene S, LeBihan D, Pallier C. 2007. Brain structure predicts the learning of foreign speech sounds. Cereb Cortex. 17:575–582.

Good CD, Johnsrude I, Ashburner J, Henson RN, Friston KJ, Frackowiak RS. 2001. Cerebral asymmetry and the effects of sex and handedness on brain structure: a voxel-based morphometric analysis of 465 normal adult human brains. Neuroimage. 14:685–700.

Griffiths TD, Warren JD. 2002. The planum temporale as a computational hub. Trends Neurosci. 25:348–353.

Hackett TA, Kaas JH. 2004. Auditory cortex in primates: functional subdivisions and processing streams. In: Gazzaniga MS, editor. The new cognitive neuroscience. 3rd ed. Cambridge (MA): MIT Press. p. 215–232.

Hackett TA, Preuss TM, Kaas JH. 2001. Architectonic identification of the core region in auditory cortex of macaques, chimpanzees, and humans. J Comp Neurol. 441:197–222.

Harasty J, Seldon HL, Chan P, Halliday G, Harding A. 2003. The left human speech-processing cortex is thinner but longer than the right. Laterality. 8:247–260.

Hickok G, Poeppel D. 2007. The cortical organization of cortical speech processing. Nat Rev Neurosci. 8:393–402.

Hogstrom LJ, Westlye LT, Walhovd KB, Fjell AM. 2012. The structure of the cerebral cortex across adult life: age-related patterns of surface area, thickness, and gyrification. Cereb Cortex [Epub ahead of print]. doi:10.1093/cercor.bhs231.

Hutsler J, Galuske RAW. 2003. The specialized structure of human language cortex: pyramidal cell size asymmetries within auditory and language-associated regions of the temporal lobes. Brain Lang. 86:226–242.

Ihnen SKZ, Church JA, Petersen SE, Schlaggar BL. 2009. Lack of generalizability of sex differences in the fMRI BOLD activity associated with language processing in adults. Neuroimage. 45:1020–1032.

Im K, Lee JM, Lee J, Shin YW, Kim IY, Kwon JS, Kim SI. 2006. Gender difference analysis of cortical thickness in healthy young adults with surface-based methods. Neuroimage. 31:31–38.

Im K, Lee JM, Lyttelton O, Kim SH, Evans AC, Kim SI. 2008. Brain size and cortical structure in the adult brain. Cereb Cortex. 18:2181–2191.

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Jamison HL, Watkins KE, Bishop DVM, Matthews PM. 2006. Hemispheric specialization for processing auditory nonspeech stimuli. Cereb Cortex. 16:1266–1275.
Jancke L, Schlaug G, Huang X, Steinmetz H. 1994. Asymmetry of the planum parietale. Neuroreport. 5:1161–1163.
Jancke L, Steinmetz H. 1993. Auditory lateralization and planum temporale asymmetry. Neuroreport. 5:169–172.
Jancke L, Wüstenberg T, Scheich H, Heinze H. 2002. Phonetic perception and the temporal cortex. Neuroimage. 15:733–746.
Josse G, Hervé PY, Crivello F, Mazoyer B, Tzourio-Mazoyer N. 2006. Hemispheric specialization for language: brain volume matters. Brain Res. 1068:184–193.
Josse G, Kherif F, Flandin G, Seghier ML, Price CJ. 2009. Predicting language lateralization from gray matter. J Neurosci. 29:13516–13523.
Kaas JH, Hackett TA. 2000. Subdivions of auditory cortex and processing streams in primates. Proc Natl Acad Sci USA. 97:11793–11799.
Knaus TA, Bollich AM, Corey DM, Lemen LC, Foundas AL. 2006. Variability in perisylvian brain anatomy in healthy adults. Brain Lang. 97:219–232.
Kuperberg GR, Broome MR, McGuire PK, David AS, Eddy M, Ozawa F, Goff D, West WC, Williams SC, van der Kouwe AJ et al. 2003. Regionally localized thinning of the cerebral cortex in schizophrenia. Arch Gen Psychiatry. 60:878–888.
Leonard CM, Towler S, Welcome S, Halderman LK, Otto R, Eckert M, Chiarello C. 2008. Size matters: cerebral volume influences sex differences in neuroanatomy. Cereb Cortex. 18:2920–2931.
Li G, Nie J, Wu G, Wang Y, Shen D. 2012. Consistent reconstruction of cortical surfaces from longitudinal brain MR images. Neuroimage. 59:3805–3820.
Liem F, Zaehle T, Burkhard A, Jancke L, Meyer M. 2012. Cortical thickness of supratemporal plane predicts auditory N1 amplitude. Neuroreport. 23:1026–1030.
Lu LH, Dapretto M, O'Hare ED, Kan E, McCourt ST, Thompson PM, Toga AW, Bookheimer SY, Sowell ER. 2009. Relationships between brain activation and brain structure in normally developing children. Cereb Cortex. 19:2595–2604.
Luders E, Gaser C, Jancke L, Schlaug G. 2004. A voxel-based approach to gray matter asymmetries. Neuroimage. 22:656–664.
Luders E, Gaser C, Narr KL, Toga AW. 2009. Why sex matters: brain size independent differences gray matter distributions between men and woman. J Neurosci. 29:14265–14270.
Luders E, Narr KL, Thompson PM, Rex DE, Jäncke L, Toga AW. 2006. Hemispheric asymmetries in cortical thickness. Cereb Cortex. 16:1232–1238.
Luders E, Narr KL, Thompson PM, Woods RP, Rex DE, Jancke L, Steinmetz H, Toga AW. 2005. Mapping cortical gray matter in the young adult brain: effects of gender. Neuroimage. 26: 493–501.
Lv B, Li J, He H, Li M, Zhao M, Ai L, Yan F, Xian J, Wang Z. 2010. Gender consistency and difference in healthy adults revealed by cortical thickness. Neuroimage. 53:373–382.
Lyttelton OC, Karama S, Ad-Dab'agh Y, Zatorre RJ, Carbonell F, Worsley K, Evans AC. 2009. Positional and surface area asymmetry of the human cerebral cortex. Neuroimage. 46:895–903.
Makris N, Pandya DN. 2009. The extreme capsule in humans and rethinking of the language circuitry. Brain Struct Funct. 213:343–358.
Meyer M, Friederici AD, von Cramon DY. 2000. Neurocognition of auditory sentence comprehension: event-related fMRI reveals sensitivity to syntactic violations and task demands. Brain Res Cogn Brain Res. 9:19–33.
Meyer M, Zaehle T, Gountouna EV, Barron A, Jäncke L, Turk A. 2005. Spectro-temporal integration during speech perception involves left posterior auditory cortex. Neuroreport. 16:1985–1989.
Meyer M, Zysset S, von Cramon DY, Alter K. 2005. Distinct fMRI responses to laughter, speech, and sounds along the human perisylvian cortex. Brain Res Cogn Brain Res. 24:291–306.
Morosan P, Rademacher J, Schleicher A, Amunts K, Schormann T, Zilles K. 2001. Human primary auditory cortex: cytoarchitectonic subdivisions and mapping into a spatial reference system. Neuroimage. 13:684–701.
Mühlau M, Rauschecker JP, Oestreicher E, Gaser C, Röttinger M, Wohlschlager AM, Simon F, Etgen T, Conrad B, Sander D. 2006. Structural brain changes in tinnitus. Cereb Cortex. 16:1283–1288.
Pandya DN. 1995. Anatomy of the auditory cortex. Rev Neurol Paris. 151:486–494.
Panizzon MS, Fennema-Notestine C, Eyler LT, Jernigan TL, Prom-Wormley E, Neale M, Jacobson K, Lyons MJ, Grant MD, Franz CE et al. 2009. Distinct genetic influences on cortical surface area and cortical thickness. Cereb Cortex. 19:2728–2735.
Patterson RD, Uppenkamp S, Johnsrude IS, Griffiths TD. 2002. The processing of temporal pitch and melody information in auditory cortex. Neuron. 36:767–776.
Penhune VB, Cismaru R, Dorsaint-Pierre R, Petitto LA, Zatorre RJ. 2003. The morphometry of auditory cortex in the congenitally deaf measured using MRI. Neuroimage. 20:1215–1225.
Penhune VB, Zatorre RJ, MacDonald JD, Evans AC. 1996. Interhemispheric anatomical differences in human primary auditory cortex: probabilistic mapping and volume measurement from magnetic resonance scans. Cereb Cortex. 6:661–672.
Price CJ. 2012. A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. Neuroimage. 62:816–847.
Rademacher J, Morosan P, Schormann T, Schleicher A, Werner C, Freund H, Zilles K. 2001. Probabilistic mapping and volume measurement of human primary auditory cortex. Neuroimage. 13:669–683.
Rakic P. 2009. Evolution of the neocortex: a perspective from developmental biology. Nat Rev Neurosci. 10:724–735.
Rakic P. 2007. The radial edifice of cortical architecture: from neuronal silhouettes to genetic engineering. Brain Res Rev. 55:204–219.
Rakic P. 2000. Radial unit hypothesis of neocortical expansion. Novartis Found Symp. 228:30–42.
Rakic P. 1995. A small step for the cell, a giant leap for mankind: a hypothesis of neocortical expansion during evolution. Trends Neurosci. 18:383–388.
Rakic P. 1988. Specification of cerebral cortical areas. Science. 241:170–176.
Rauschecker JP, Tian B, Hauser M. 1995. Processing of complex sounds in the macaque nonprimary auditory cortex. Science. 268:111–114.
Rauschecker JP, Tian B, Pons T, Mishkin M. 1997. Serial and parallel processing in rhesus monkey auditory cortex. J Comp Neurol. 382:89–103.
Rosas HD, Liu AK, Hersch S, Glessner M, Ferrante RJ, Salat DH, van der Kouwe A, Jenkins BG, Dale AM, Fischl B. 2002. Regional and progressive thinning of the cortical ribbon in Huntington's disease. Neurology. 58:695–701.
Rosen GD. 1998. Cellular, morphometric, ontogenetic and connectional substrates of anatomical asymmetry. Neurosci Biobehav Rev. 20:773–780.
Salat DH, Buckner RL, Snyder AZ, Greve DN, Desikan RS, Busa E, Morris JC, Dale AM, Fischl B. 2004. Thinning of the cerebral cortex in aging. Cereb Cortex. 14:721–730.
Schneider P, Andermann M, Wengenroth M, Goebel R, Flor H, Rupp A, Diesch E. 2009. Reduced volume of Heschl's gyrus in tinnitus. Neuroimage. 45:927–939.
Schneider P, Scherg M, Dosch HG, Specht HJ, Gutschalk A, Rupp A. 2002. Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. Nat Neurosci. 5:688–694.
Shapleske J, Rossell SL, Woodruff PWR, David AS. 1999. The planum temporale: a systematic, quantitative review of its structural, functional and clinical significance. Brain Res Rev. 29:26–49.
Sigalovsky IS, Fischl B, Melcher JR. 2006. Mapping an intrinsic MR property of gray matter in auditory cortex of living humans: a possible marker for primary cortex and hemispheric differences. Neuroimage. 32:1524–1537.
Sowell ER, Peterson BS, Kan E, Woods RP, Yoshi J, Bansal R, Xu D, Zhu H, Thompson PM, Toga AW. 2007. Sex differences in cortical thickness mapped in 176 individuals between 7 and 87 years of age. Cereb Cortex. 17:1550–1560.

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Sowell ER, Thompson PM, Leonard CM, Welcome SE, Kan E, Toga AW. 2004. Longitudinal mapping of cortical thickness and brain growth in normal children. J Neurosci. 24:8223–8231.
Steinmetz H. 1996. Structure, function and cerebral asymmetry: in vivo-morphometry of the planum temporale. Neurosci Biobehav Rev. 20:587–591.
Tahmasebi AM, Davis MH, Wild CJ, Rodd JM, Hakyemez H, Abolmaesumi P, Johnsrude IS. 2012. Is the link between anatomical structure and function equally strong at all cognitive levels of processing? Cereb Cortex. 22:1593–1603.
Takahashi R, Ishii K, Kakigi T, Yokoyama K. 2011. Gender and age differences in normal adult human brain: voxel-based morphometric study. Hum Brain Mapp. 32:1050–1058.
Takao H, Abe O, Yamasue H, Aoki S, Sasaki H, Kasai K, Yoshioka N, Ohtomo K. 2011. Gray and white matter asymmetries in healthy individuals aged 21–29 years: a voxel-based morphometry and diffusion tensor imaging study. Hum Brain Mapp. 32: 1762–1773.
Tamnes CK, Østby Y, Fjell AM, Westlye T, Due-Tønnessen P, Walhovd KB. 2010. Brain maturation in adolescence and young adulthood: regional age-related changes in cortical thickness and white matter volumes and microstructure. Cereb Cortex. 20: 534–548.
Toro R, Perron M, Pike B, Richer L, Veillette S, Pausova Z, Paus T. 2008. Brain size and folding of the human cerebral cortex. Cereb Cortex. 18:2352–2357.
Tzourio-Mazoyer N, Josse G, Crivello F, Mazoyer B. 2004. Interindividual variability in the hemispheric organization for speech. Neuroimage. 21:422–435.
van Soelen IL, Brouwer RM, van Baal GC, Schnack HG, Peper JS, Collins DL, Evans AC, Kahn RS, Boomsma DI, Hulshoff Pol HE. 2012. Genetic influences on thinning of the cerebral cortex during development. Neuroimage. 59:3871–3880.
Vargha-Khadem F, Watkins KE, Price CJ, Ashburner J, Alcock KJ, Connelly A, Frackowiak RSJ, Friston KJ, Prembrey ME, Mishkin M et al. 1998. Neural basis of an inherited speech and language disorder. Proc Natl Acad Sci USA. 95:12695–12700.
Warren JD, Uppenkamp S, Patterson RD, Griffiths TD. 2003. Separating pitch chroma and pitch height in the human brain. Proc Natl Acad Sci USA. 100:10038–10042.
Watkins KE, Paus T, Lerch JP, Zijdenbis A, Collins DL, Neelin P, Taylor J, Worsley KJ, Evans AC. 2001. Structural asymmetries in the human brain: a voxel-based statistical analysis of 142 MRI. Cereb Cortex. 11:868–877.
Watkins KE, Vargha-Khadem F, Ashburner J, Passingham RE, Conelly A, Friston KJ, Frackowiak RSJ, Mishkin M, Gadian DG. 2002. MRI analysis of an inherited speech and language disorder: structural brain anomalies. Brain. 125:465–478.
Westbury CF, Zatorre RJ, Evans AC. 1999. Quantifying variability in the planum temporale: a probability map. Cereb Cortex. 9:392–405.
Winkler AM, Kochunov P, Blangero J, Almasy L, Zilles K, Fox PT, Duggirala R, Glahn DC. 2010. Cortical thickness or grey matter volume? The importance of selecting the phenotype for imaging genetics studies. Neuroimage. 53:1135–1146.
Woods DL, Herron TJ, Cate AD, Yund EW, Stecker GC, Rinne T, Kang X. 2010. Functional properties of human auditory cortical fields. Front Syst Neurosci. 4:155.
Zaehle T, Geiser E, Alter K, Jancke L, Meyer M. 2008. Segmental processing in the human auditory dorsal pathway. Brain Res. 1220:179–190.
Zaehle T, Wüstenberg T, Meyer M, Jancke L. 2004. Evidence for rapid auditory perception as the foundation of speech processing—a sparse temporal sampling fMRI study. Eur J Neurosci. 20:2447–2456.
Zatorre RJ, Belin P. 2001. Spectral and temporal processing in human auditory cortex. Cereb Cortex. 11:946–953.

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